4D-Var Data Assimilation for Navy Mesoscale NWP

Liang Xu
Naval Research Laboratory
Monterey, CA 93943-5502
phone: (831) 656-5159 fax: (831) 656-4769 email: liang.xu@nrlmry.navy.mil

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LONG-TERM GOALS

The long-term goal of this Rapic Transition Process (RTP) project is to provide the warfighter with superior battlespace environmental awareness in terms of high fidelity four-dimensional (4D) depiction of the regional/mesoscale atmospheric states. This situational awareness is a key aspect of information superiority in the DoD's strategic plan to ensure battlespace dominance in the 21st century. This goal is to be accomplished by providing COAMPS® with the best possible initial condition through the development and use of a next generation mesoscale atmospheric 4D variational (4D-Var) data assimilation system, COAMPS®/NAVDAS-AR (Accelerated Representer), or COAMPS®-AR for short.

OBJECTIVES

The objective of this project is to develop and transition an operational 4D-Var mesoscale atmospheric data assimilation system to Fleet Numerical Meteorology and Oceanography Center (FNMOC). It has been well established that accurate initial conditions play a critical role in the performance of a numerical prediction (NWP) system. The Navy's operational mesoscale prediction system, Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS®), is running in more than 60 regions globally to provide mission-essential, short-term predictions of the environmental conditions. COAMPS® currently uses the three-dimensional NRL Atmospheric Variational Data Assimilation System (NAVDAS). The new data assimilation system, COAMPS®-AR, merges temporally-evolved model fields with observations to provide the best state estimate and initial conditions for COAMPS®. The successful outcome of the project will be the first operational, weak constraint, 4D-Var mesoscale atmospheric data assimilation system for the Navy. In this context, "weak constraint" means that the atmospheric forecast model is not considered a "perfect" model, but rather is assumed to have errors. COAMPS®-AR will provide high fidelity, dynamically-consistent analyses for numerical weather prediction model initialization and for warfighter support, and will be capable of efficiently handling large numbers of observations that may be irregularly distributed in space and time, and/or indirectly related to the model state variables (e.g., satellite radiances or satellite retrievals of integrated water vapor). These features of COAMPS®-AR should enable the most optimal solution (best analysis) for the initialization of the COAMPS® forecast model and improve the subsequent mesoscale numerical weather forecasts.

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APPROACH

Our approach is to build the mesoscale 4D-Var data assimilation system on the NAVDAS-AR framework (Xu et al. 2005) that has been developed and successfully applied to the global 4D-Var data assimilation using the Navy Operational Global Atmospheric Prediction System (NOGAPS) model, now NAVGEM, as a dynamic constraint. The NAVDAS-AR system, funded in part by a previous RTP, was successfully transitioned to FNMOC on 23 September 2009, and has significantly improved the forecast skill of the Navy's global NWP system. This project, which is a follow-up to a NRL ongoing in-house 6.2 mesoscale data assimilation project, has been employing the NAVDAS-AR framework to develop an operationally feasible next-generation mesoscale data assimilation system. The system has been thoroughly tested using scientific studies, and comprehensive data assimilation and forecast experiments. Although the goals were ambitious, they now become reality because the theoretical basis and some of the framework for the project were already in place owing to great progress made in our 6.1 and 6.2 in-house data assimilation projects and NAVDAS-AR RTP project.

WORK COMPLETED

The following is a list of work completed related to this project during FY13.

1. Developed and tested infrastructures that enabled the continuous update cycles of COAMPS®-AR with verifications for COAMPS® forecasts.
2. Improved the computational efficiency and scalability of COAMPS®-AR, which enables it to be used for operational purposes.
3. Enabled the assimilation of all convectional and selected satellite observations through developing and testing various observation operators and the associated Jacobians in COAMPS®-AR.
4. Put infrastructures in place that can be used assimilation of additional remotely sensed observations, such as satellite and UAV observations.
5. Improved the COAMPS® 12 and 24 hr forecasts using COAMPS®-AR instead of using the current operational 3D-Var, NAVDAS, to produce the initial conditions .
6. Moved COAMPS®-AR from HPC to FNMOC's a4au, the targeting ops computer.
7. COAMPS®-AR is on schedule to reach TRL6 by end of FY13.

These FY13 accomplishments are critical for the subsequent AMOP transition of COAMPS®-AR to FNMOC.

RESULTS

We have accelerated the development and testing of COAMPS®-AR framework due to the solid foundation we developed in the previous two years. We significantly improved the computational efficiency and scalability of COAMPS®-AR by redesign the framework earlier this year. The following results represent two highlights of the several significant accomplishments, which are essential for the transition COAMPS®-AR to FNMOC, of this project during FY13.

New capability of continuous atmospheric data assimilation update cycles in any region around the world

One of the key requirements of the operational mesoscale atmospheric data assimilation system is its capability to provide continuous data assimilation update cycles at a oment of notice in any region around the world. Figure 1 and Fingure 2 display two examples of temperature analysis increments at 2.3 km above the ground surface over the western United States and over the south eastern Asia during a 6-hr update cycle obtained using COAMPS®-AR, respectively. The results demonstrate the capability of COAMPS®-AR to be setup and operated to conduct continuous atmospheric mesoscale data assimilation in any location around the world. This enabled capability is essential for COAMPS®-AR to be used for operational purposes.

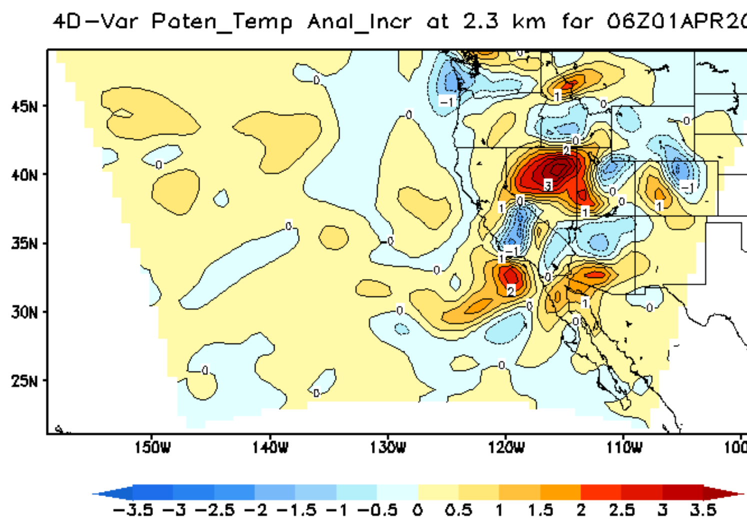

Figure 1 Potential temperature analysis increments at 2300 meters above the ground surface, western United States at 06Z on April 1st 2012 from COAMPS®-AR

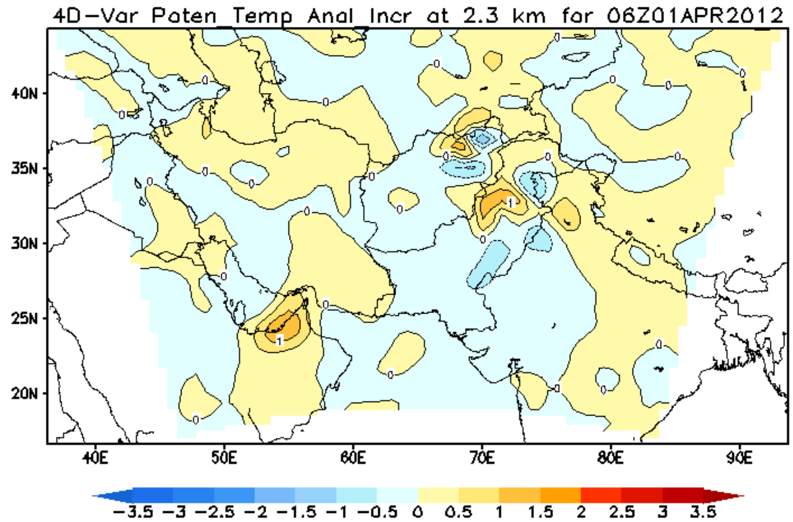

Figure 2 Potential temperature analysis increments at 2300 meters above the ground surface, southeastern Asia, at 06Z on April 1st 2012 from COAMPS®-AR

Analyses from COAMPS®-AR produce overall better COAMPS® forecast

The goal of COAMPS®-AR is to improve the overall forecast skill of COAMPS® by providing the improved initial conditions for COAMPS®. Two numerical experiments were setup to investigate the impact of two different mesoscale atmospheric data assimilation algorithms, namely NAVDAS (3D-Var) and COAMPS®-AR (4D-Var), on the forecast skills of COAMPS® during a 6-hour data assimilation/forecast update cycling for 30 days starting 06Z April 2012 in the western United States. Although we tried our best to make the inputs for the two numerical experiments as close as possible, the inputs are different for the 3D-Var and 4D-Var runs, due to the design difference, respectively. In experiment 1, the 3D-Var, NAVDAS, was used to assimilate all the observations and to provide the initial conditions for all subsequent COAMPS® forecasts. In experiment 2, the 4D-Var, COAMPS®-AR, was used to assimilate all the observations and to provide the initial conditions for all subsequent COAMPS® forecasts. As indicated in Figure 3, NAVDAS uses a halo region that allows the assimilation of additional observations outside of the actual computational (or model) domain of COAMPS®, while the 4D-Var doesn't use the additional halo region. Figure 3 highlights the design difference in using observations between NAVDAS and COAMPS®-AR.

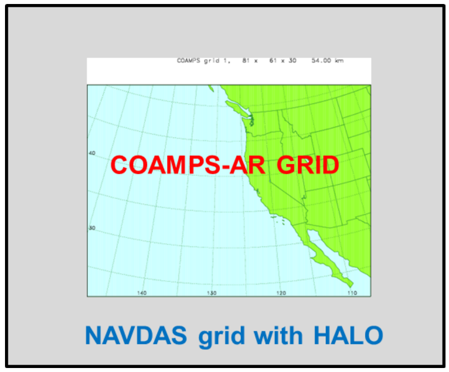

Figure 3 Difference in the areas where observations are used between NAVDAS and COAMPS®-AR. The 4D-Var only utilizes about 60 – 80% of the total number of observations used in the 3D-Var in two experiments presented here.

Our stratigy for COAMPS®-AR is that we always conduct the data assimilation minimization on the 1^{st} nest/mesh (or the coarsest nest) using the incremental 4D-Var algorithm. The impacts of the finer resolutions are accounted for through the use of finer resolution background fields predicted by the prvious COAMPS® forecasts during the calculation of the innovation vector. Consequently, all the high resolution information is included in the final analysis increments that are then added back to the coresponding COAMPS® background. We assimilate the following observations: u, v, T, prh (pseudo relative humidity), tpw (total precipitable water), and wind speed measurements in COAMPS®-AR and NAVDAS, respectively. It is important to notice that NAVDAS assimilates more observations than COAMPS®-AR does due to the HALO region. Although COAMPS®-AR only utilizes 60-80% of the total number of observations used in NAVDAS, it assimilates the observations at the right place and time using COAMPS® as a dynamical constraint. The 12-hr and 24-hr COAMPS® forecasts started from initial conditions provided by both NAVDAS and COAMPS®-AR were then verified against the available observations validated at the forecast times. The accumulated verification statistics were then collected and plotted. Figures 4a, 4b, 5a, 5b, 6a, and 6b are the verification statistics (30 days average) for COAMPS® 12-hr and 24-hr forecasts for the heights, temperature, and wind speed, respectively.

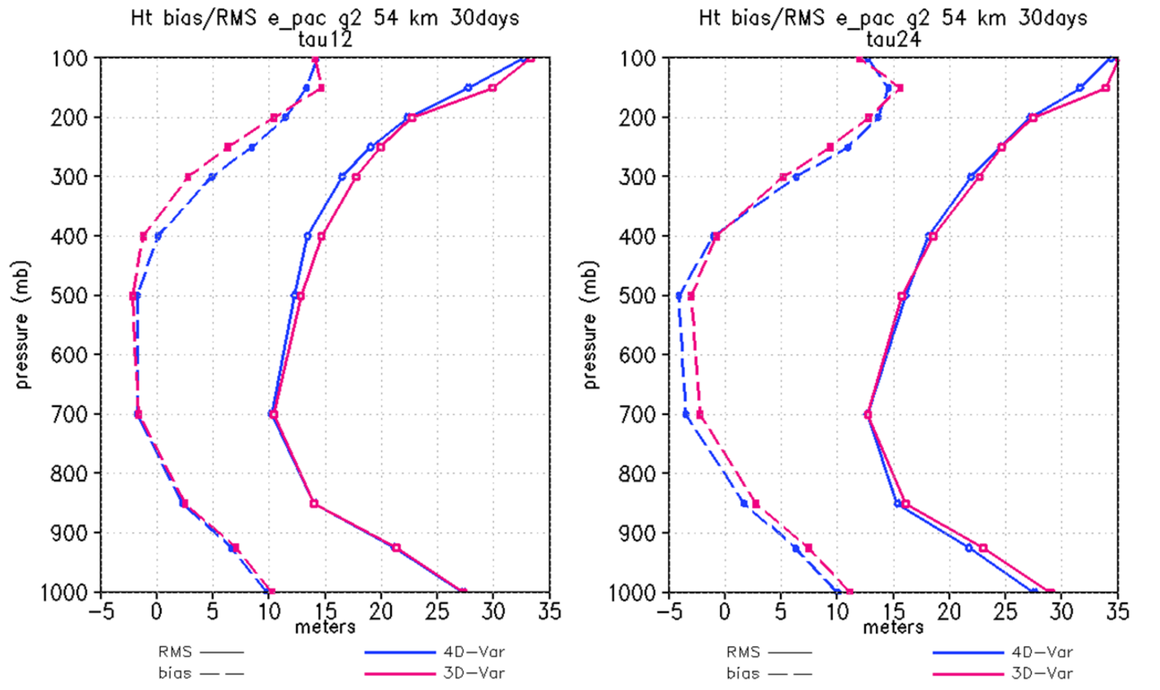

Figure 4 Verification statistics (30 days) of COAMPS® height forecast 12-hr (4a: left panel) and 24-hr (4b: right panel). The solid lines are for RMS errors while the dash lines are for bias. COAMPS® performs better using 4D-Var (blue lines) the using 3D-Var (red lines).

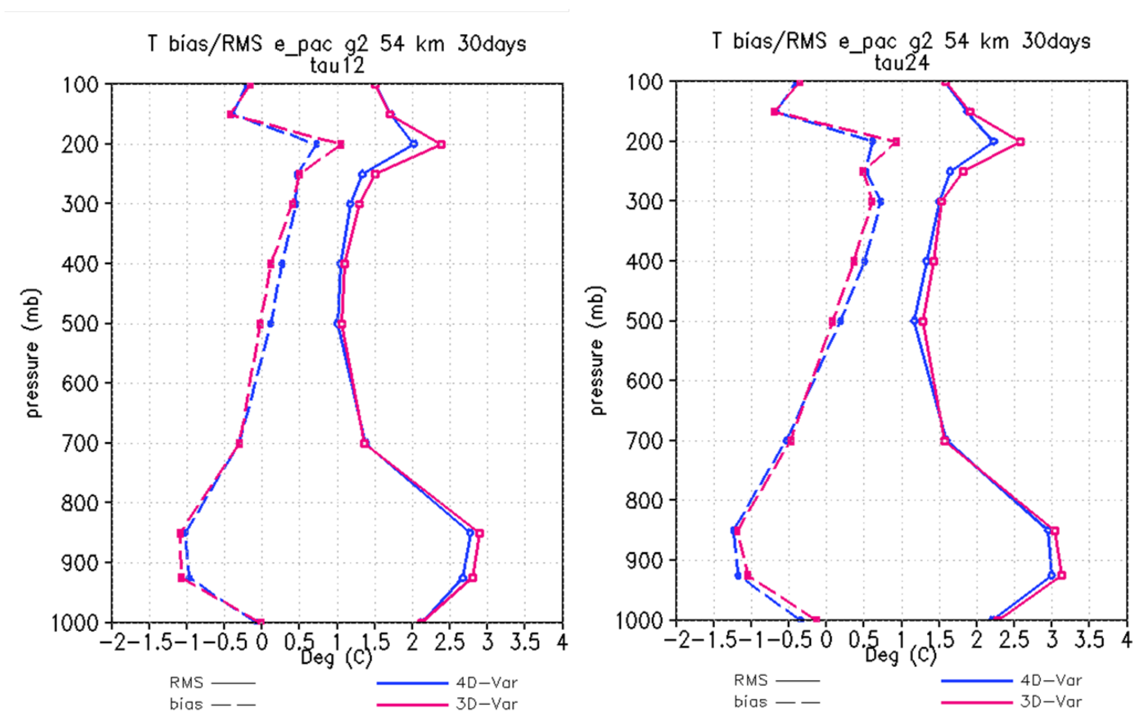

Figure 5 Verification statistics (30 days) of COAMPS® temperature forecast 12-hr (5a: left panel) and 24-hr (5b: right panel). The solid lines are for RMS errors while the dash lines are for bias. COAMPS® performs better using 4D-Var (blue lines) the using 3D-Var (red lines).

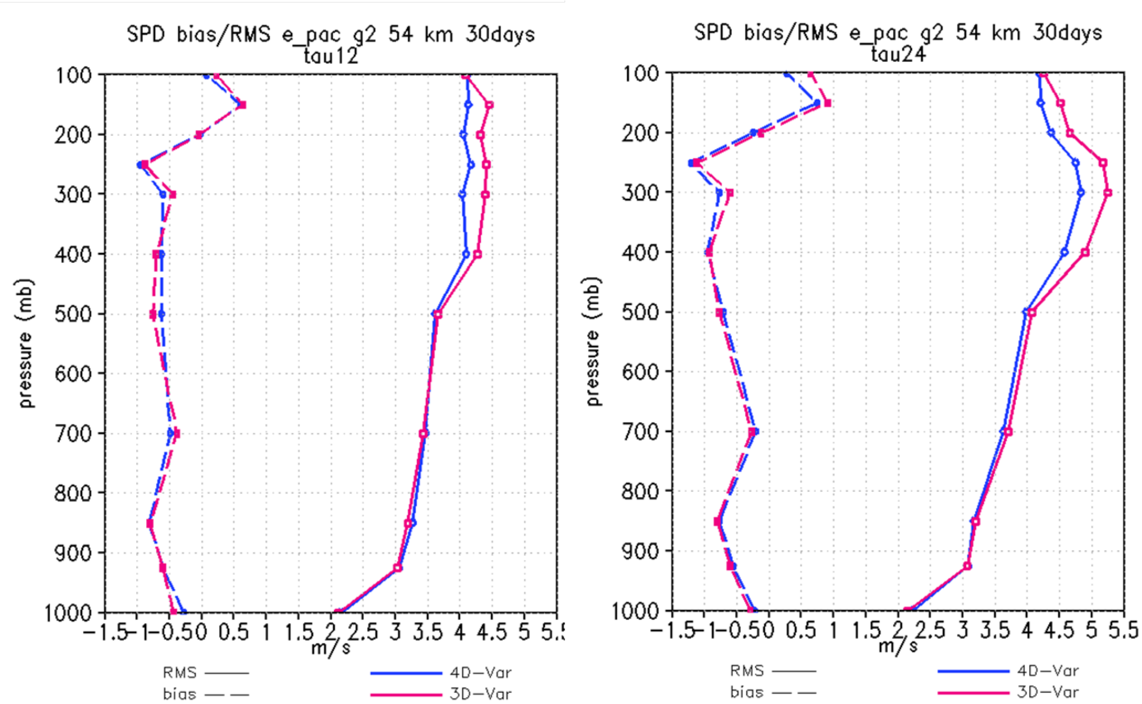

Figure 6 Verification statistics (30 days) of COAMPS® wind speed forecast 12-hr (4a: left panel) and 24-hr (4b: right panel). The solid lines are for RMS errors while the dash lines are for bias. COAMPS® performs better using 4D-Var (blue lines) the using 3D-Var (red lines).

Preliminary results based on the 30-day COAMPS® verification statistics in the western United States suggest that COAMPS®-AR improves COAMPS® 12 and 24 hrs forecasts as compared to using NAVDAS. Additional extensive data assimilation experiments for different computational domains are underway to further compare the impact of 3D-Var and 4D-Var on COAMPS® forecasts.

IMPACT/APPLICATIONS

The current operational mesoscale atmospheric data assimilation system at FNMOC, NAVDAS, is based on a 3D-Var algorithm and is cast in observation space. The 3D-Var algorithm is widely used in intermittent update cycling data assimilation for the analysis of mesoscale atmospheric data assimilatiuon around the world. It can handle relatively slowly evolving flows and observation platforms that sample heterogeneously in space, but assume that the observations are taken at the analysis time. However, highly intermittent flows that are not governed by simple balance relationships, and observation systems that sample irregularly in time, or with high temporal frequency, are not well accommodated within an intermittent 3D-Var framework but can be accommodated by a 4D-Var data assimilation system. Furthermore, an intermittent 3D-Var algorithm produces a “snapshot” of the atmosphere at the center of the typical 6-hour observation time window, automatically making the resulting atmospheric analysis at least 3 hours old.

With COAMPS®-AR, a continuous picture of the regional atmosphere over the observation time window is produced, providing an atmospheric analysis at any given time of the time window rather than 3 hours old. Although NAVDAS has been quite successful, a 4D data assimilation system is a necessity to significantly improve not only the accuracy of the common operational picture required by the warfighter but also the timeliness of providing this more accurate picture to the warfighter. The

advanced 4D-Var mesoscale data assimilation algorithm, COAMPS®-AR, will provide the basis for this system. Only through 4D-Var algorithms can we truly exploit many of the observations from current and future observing systems. This is especially important for remotely sensed observations that are nonlinearly and indirectly related to the model state variables (e.g., satellite radiances and GPS radio occultation measurements). In addition, the computational efficiency of COAMPS®-AR with respect to the number of observations makes it more efficient than the NAVDAS system in handling the monumental increase in the volume of satellite data expected over the next decade.

TRANSITIONS

We transitioned the significantly improved COAMPS®-AR framework to the 6.4 component of this RTP project. We also started the process to transition COAMPS®-AR to FNMOC.

RELATED PROJECTS

The current project will be merged into the PMW-120 atmospheric data assimilation project in FY14.

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PUBLICATIONS

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